NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

INITIAL DESIGN AND CONCEPT OF OPERATIONS FOR A CLANDESTINE DATA RELAY UUV TO CIRCUMVENT JUNGLE CANOPY EFFECTS ON SATELLITE COMMUNICATIONS

by

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September 2011

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REPORT DOCUMENTATION PAGE		*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.		

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE September 2011	3. REPORT TYPE AND DATES COVERED Master's Thesis
4. TITLE AND SUBTITLE Initial Design and Concept of Operations for a Clandestine Data Relay UUV To Circumvent Jungle Canopy Effects on Satellite Communications		**5. FUNDING NUMBERS**
6. AUTHOR(S) Michael G.Tyree		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _____N/A_____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)
Communications within jungle environments has always been a difficult proposition. This is especially true of collection assets beneath triple canopy jungle that need to communicate with overhead national assets. The traditional methods of countering the negative effects of the canopy on EM signals have been to increase the power to offset the losses, or to utilize new, more canopy transparent portions of the EM spectrum. However, there are complications with both of these methods. Simply increasing transmitted power increases the drain on the system's power supply, thus lowering effective on-station time. Shifting to a different portion of the EM spectrum can negatively affect the transmission rate of the system and requires specialized equipment such as antennas and modulators. This work addresses the issue by designing a semi-autonomous UUV, which will clandestinely relay data from the embedded jungle systems to overhead national assets. Rather than trying to punch through the canopy directly, the proposed UUV will take advantage of the fact that most jungle water ways have, at the very least, a thinner canopy overhead if not a clear view of the sky for less lossy satellite communications. This shifts the primary communications from an Earth-Sky problem to a lateral wave model where the communications travels parallel to the canopy. While the jungle is still not an ideal medium for communications, other methods can be used to address these losses. The proposed UUV will be designed to be cheap and constructed from existing systems. It will also be small, and lightweight, enough to be delivered and deployed in theater via aircraft, boats, and operators on the ground. Additionally it will be capable of long on station times due to the ability recharge on station.

14. SUBJECT TERMS AUV, UUV, Jungle Operations, Data Relay, Clandestine Operations			15. NUMBER OF PAGES 91
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN INFORMATION WARFARE SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Communications within jungle environments has always been a difficult proposition. This is especially true of collection assets beneath triple canopy jungle that need to communicate with overhead national assets. The traditional methods of countering the negative effects of the canopy on EM signals have been to increase the power to offset the losses, or to utilize new, more canopy transparent portions of the EM spectrum. However, there are complications with both of these methods. Simply increasing transmitted power increases the drain on the system's power supply, thus lowering effective on-station time. Shifting to a different portion of the EM spectrum can negatively affect the transmission rate of the system and requires specialized equipment such as antennas and modulators. This work addresses the issue by designing a semi-autonomous UUV, which will clandestinely relay data from the embedded jungle systems to overhead national assets. Rather than trying to punch through the canopy directly, the proposed UUV will take advantage of the fact that most jungle water ways have, at the very least, a thinner canopy overhead if not a clear view of the sky for less lossy satellite communications. This shifts the primary communications from an Earth-Sky problem to a lateral wave model where the communications travels parallel to the canopy. While the jungle is still not an ideal medium for communications, other methods can be used to address these losses. The proposed UUV will be designed to be cheap and constructed from existing systems. It will also be small, and lightweight, enough to be delivered and deployed in theater via aircraft, boats, and operators on the ground. Additionally it will be capable of long on station times due to the ability recharge on station.

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LIST OF ACRONYMS AND ABBREVIATIONS

AES   Advanced Encryption Standard

AI   Artificial Intelligence

ASCL   Autonomous Systems and Controls Laboratory

AUV   Autonomous Underwater Vehicle

CDMA   Code Division Multiple Access

CEP   Circular Error Probable

CONOPS   Concept of Operations

COTS   Commercial off the Shelf

CSS   Central Security Service

FDMA   Frequency Division Multiple Access

GPS   Global Positioning System

JTRS   Joint Tactical Radio System

LIDAR   Light Detection and Ranging

MIMO   Multiple Input, Multiple Output

NISP   National Industrial Security Program

NIST   National Institute of Standards and Technology

NSA   National Security Agency

RAM   Random Access Memory

ROM   Read Only Memory

SIGINT   Signals Intelligence

SISO   Single Input, Single Output

SOF   Special Operations Forces

TDMA   Time Division Multiple Access

USB	Universal Serial Bus
UUV	Unmanned Underwater Vehicle
VoiP	Voice Over Internet Protocol

ACKNOWLEDGMENTS

First, I would like to thank my two advisors, Dr. Buettner and Sean Kragelund. If you think something in here is a really good idea, I probably got it from them.

Next, I would like to thank my wife Kathrine for putting up with the long hours that went along with this degree. I know this was supposed to be a shore tour, but at least I had the weekends.

Finally, I would like to thank my fellow classmates in the IW program. This whole process was a team sport.

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I. INTRODUCTION

A. THE OPERATING ENVIRONMENT

The modern era of conflict is defined by the large number of low intensity, asymmetrical conflicts distributed around the world. Whether these threats are Islamic extremists in Indonesia's Aceh province, the more "classical" Maoist insurgents in eastern India, or cartels and narco-terrorists of the Amazon river valley, they all share a number of things in common, number one among them being the desire to remain hidden.

To that end, the jungles of many of the world's hot spots offer the perfect safe haven for those wishing to remain hidden from a larger and stronger force. This idea has been borne out through centuries of warfare, and is no stranger to the United States given its experiences during the Vietnam War, the Philippine Insurrection, and the many island campaigns of World War II. Combating an enemy entrenched beneath a thick jungle canopy requires extensive efforts by a nation's military and intelligence assets.

There are few environments on Earth as challenging to military and intelligence operations as the jungle. This is especially true in the information age where the austere surroundings impede, or even nullify, the United States' primary force enablers of communications, data collection, and networking. In particular, the triple canopy of the jungle is nearly impenetrable to the myriad of satellites and airborne assets, which the U.S. has traditionally used for data collection and relay. Until now, the push has been to develop canopy-penetrating technology, which has seen limited success in the areas of LIDAR imaging of terrain from airborne assets. However, that is insufficient for a number of data collection systems such as small, ground based, signals intelligence (SIGINT) sensors that need to transmit back to space borne national assets.

B. DEFINING THE ENVIRONMENT

For the purposes of this work, the word jungle will be synonymous with rainforest, and will be used interchangeably. By definition, the rainforest is one of the

Earth's major biomes, and is further subdivided into *tropical rainforest* and *temperate rainforest*. These subtypes share the qualities of and an enormous density of vegetation, and a high amount of annual rainfall.

The primary difference between the two subtypes is their location. Tropical rainforest is found along the equator, primarily between 28º North and South latitude. Between the two, tropical rainforest is the harsher medium for communications technology. Due to relatively high temperatures year round, combined with 2 to 10 meters of annual rainfall, they are generally very humid. Additionally, the canopy of tropical rainforest is typically much denser than that of temperate rainforest, dense enough that it can actually prevent rainfall from reaching the ground in some places.

C. CIRCUMVENTING THE CANOPY

Given the profound effect that thick canopies can have on Earth-Space communications, this work explores methods to eliminate the canopy from the problem by taking advantage of the numerous waterways and rivers that cut through the world's jungles and rainforests. The main bodies of these waterways are normally marked by an unobstructed view of the sky making them much more preferable for Earth-Space communications systems.

By creating an unmanned underwater vehicle (UUV) that can act as a data relay between a system in the jungle, and its satellite component, the problem of trying to overcome the attenuation of the canopy can be avoided. Instead it is replaced with a relatively simpler lateral wave problem between the embedded jungle system and the UUV. This is illustrated in Figure 3.
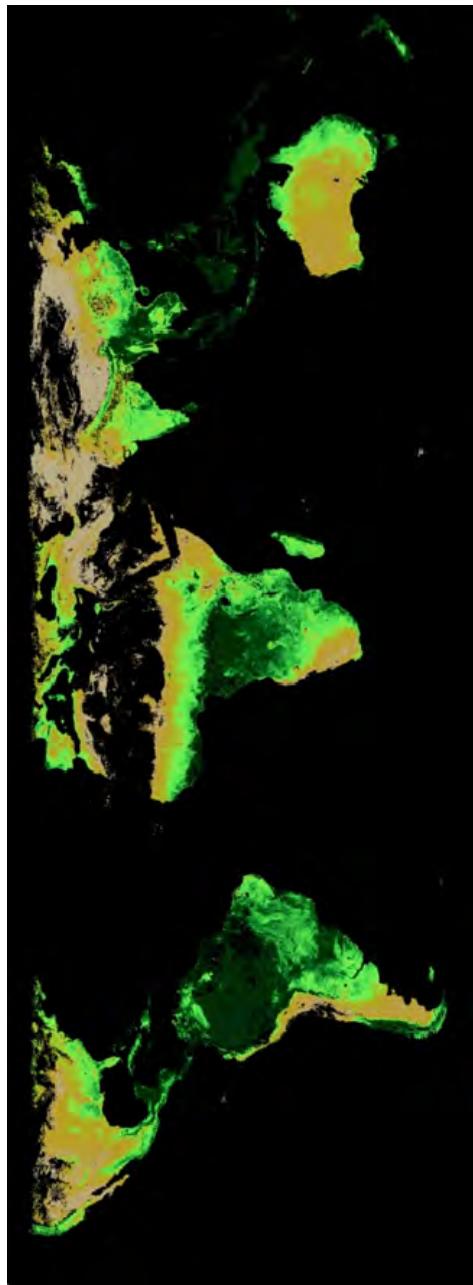
Figure 1.   Leaf coverage index from NASA's NEO program. The darker the green, the denser the foliage cover. Tropical rainforests are the darkest areas, corresponding to on average of 7 m^2 of leaves per m^2 of ground. (From [1])

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[1] National Aeronautics and Space Administration NEO Website, "NEO: NASA Earth Observations. August 16, 2011," National Aeronautics and Space Administration http://neo.sci.gsfc.nasa.gov/Search.html?group=21.
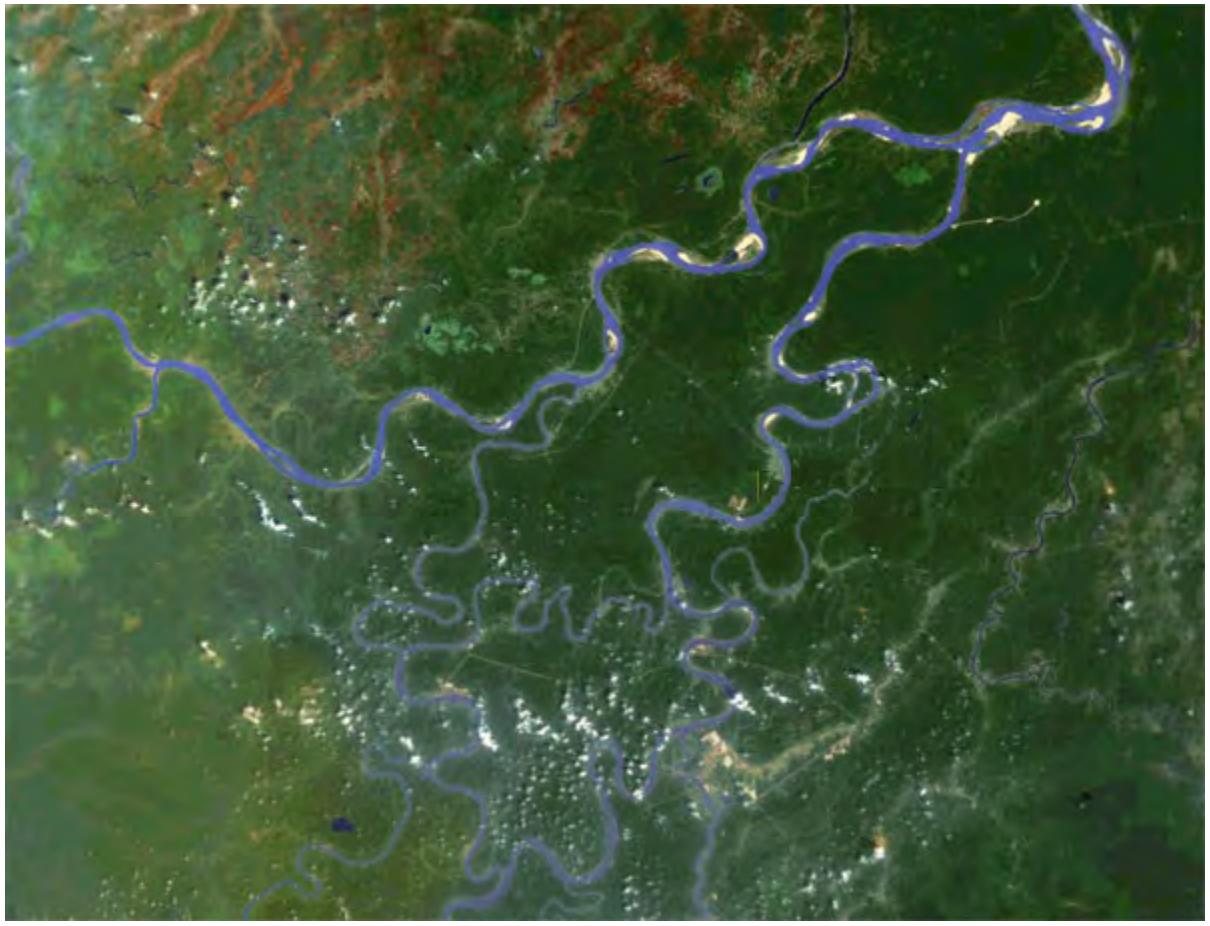
Figure 2.   A picture of the Niger River Delta as seen from space. Approximately 8.5% of the visible area in this picture is the river. (From [2])

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2 Mongabay.com, "Rainforests", Rhett Butler, http://rainforests.mongabay.com/0603.htm.
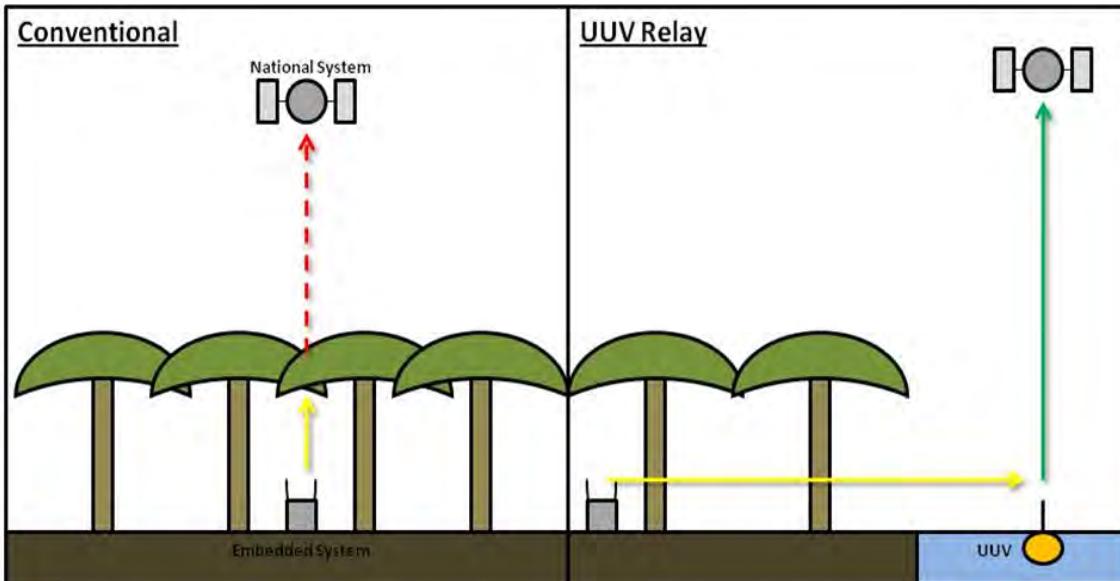
Figure 3.   Conceptual figure for the use of a data relay UUV.

D.   THE LATERAL WAVE PROBLEM

The defining work on radio wave propagation in the jungle was done by Theodor Tamir, and is summarized in a number of papers on the subject.[3,4,5] He used a theoretical model commonly referred to as the dielectric slab model, or simply, "the slab model". The slab model assumes the jungle acts as a lossy dielectric slab laid over flat ground. From this, Dr. Tamir concluded that there are only three paths that a communications signal in a forest environment can take[6]:

- A direct line-of-sight wave and reflected waves

- A sky wave that is due to a single hop reflection from the ionosphere

[3] Theodor Tamir, "Lateral Wave Applications to Radio Systems." (Paper presented at the Workshop on Radio Systems in Forested and/or Vegetated Environments for Army Communications Command, Fort Huachuca Arizona, February 1974. 23–30).

[4] Theodor Tamir, "On Radio-Wave Propagation in Forested Environments," *IEEE Transactions on Antennas and Propagation* (1967): 23-30.

[5] Theodor Tamir, "Radio Wave Propagation Along Mixed Paths in Forest Environments." *IEEE Transactions on Antennas and Propagation* (1977): 471–477.

[6] Tamir, *Lateral Wave Applications*, 25.

- A lateral wave that travels mostly in the air region by skimming along the canopy

These communications paths are illustrated in Figure 4.
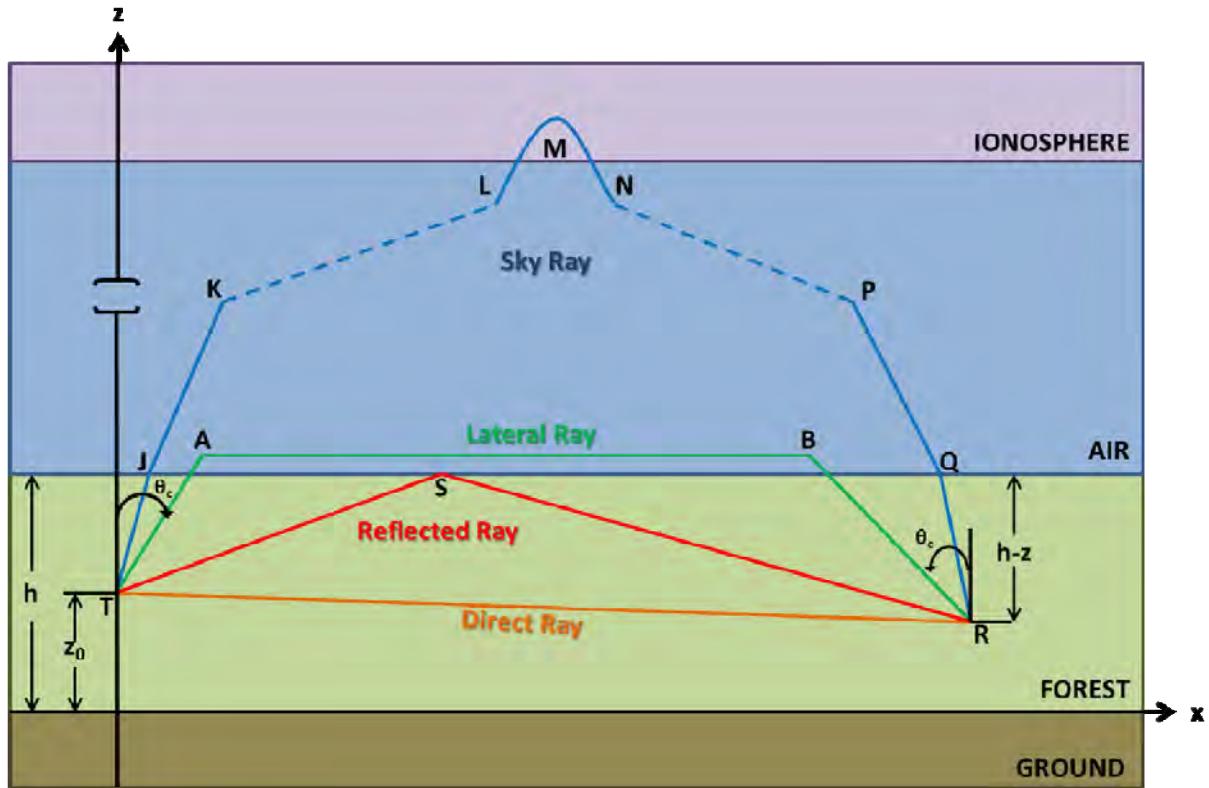
Figure 4.   Idealized planar geometry of a forest environment, of Tamir's *Lateral Wave Applications to Radio Systems*, reproduced here for clarity. The three communications pathways are Direct and Reflected (TR and TSR respectively), Sky (TJKLMNPQR), and Lateral (TABR). The angle θ_c is the critical angle of total reflection within the forest slab. (From [7])

Due to the reflected and direct rays travelling through a lossy medium, they both decay exponentially as a function of distance, which limits their effects at the receiver. Since both the sky ray and the lateral ray both travel in air, they are less attenuated over long distances. However, due to the relatively narrow frequency range of ionospheric

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[7] Tamir, *Lateral Wave Applications*, 25.

reflection (approximately 3 to 10 MHz), and the much longer path length relative to the lateral ray path, Tamir concludes that the lateral wave is the dominant path at distances of practical importance.[8]

According to Tamir, this horizontal mode of travel arises from the summation of a system of random scatterers, which are small relative to the signal's wavelength (i.e., trunks, branches, leaves). In this system, the numerous random scatterings add constructively laterally away from the source.[9]

While lateral wave transmission in the jungle experiences much less attenuation then vertical transmission through the canopy, it is not without rather large losses. Tamir's work with the slab model identified four main sources of loss in lateral wave transmission:

Initial Loss (L_o): A function of the spreading of the transmitted wave.

Separation Loss (L_s): Proportional to the separation between the transmitting and receiving antennas and the air-forest interface. It arises from the longer path the wave must take to get to the air-forest interface.

Interference Loss (L_i): Inversely proportional to the distance of the transmitting and receiving antennas from the ground. Thus, the lower the antennas are the larger this loss.

Resistance Loss (L_r): A result of the resistivity of an antenna changing with proximity to the ground. It is inversely proportional to the distance of the transmitting and receiving antennas from the ground. Thus, the lower the antennas are the larger this loss.

As is clear from their descriptions, the last three loss types (L_s, L_i, L_r) are higher if one, or both, antennas are close to the ground, thus the traditional method of increasing the effectiveness of a lateral wave communications system is to raise the antennas as high as possible. Obviously, raising the antenna above the ground isn't an option for the UUV

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[8] Tamir, *Lateral Wave Applications*, 25.

[9] *Ibid.* , 26.

proposed here, but it is certainly a consideration when placing the embedded, in-jungle system. Additionally, there are other methods to mitigate some of the losses in a scatter rich environment such as the rainforest.

E. MULTIPLE INPUT, MULTIPLE OUTPUT (MIMO)

Given that raising the UUV antenna in order to decrease losses is not an option, alternative methods to counter the losses must be found. One such method of countering channel fading is the use of MIMO, which increases channel capacity over traditional systems as well as improved reception in scatter and fading rich environments. MIMO has two properties that make that possible: *spatial multiplexing* and *transmission diversity*.

1. Basics

Before delving further into the specifics of the benefits of MIMO, the basic structure must be discussed. Figure 5 represents a nominal MIMO communications system with n transmitting antennas ($n_t = n$) and m receiving antennas ($n_r = m$).
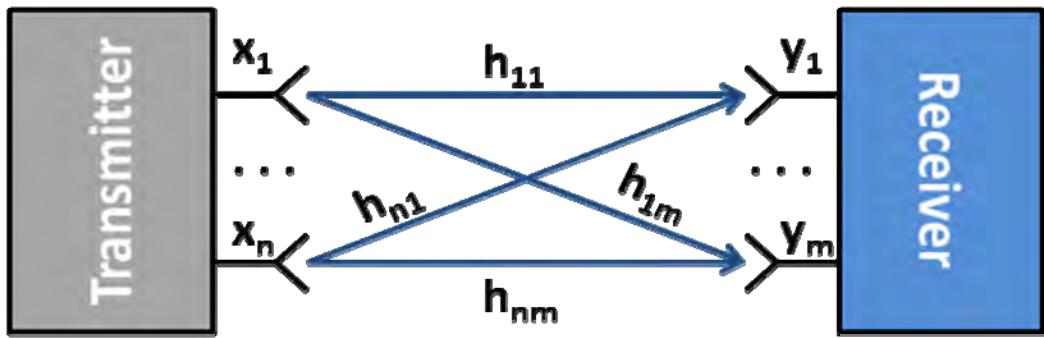
Figure 5.   A basic MIMO system.

The *h* vectors in this diagram represent the various channels between each transmitting and receiving antenna. These are based on the scattering environment between the two, and will most likely not be uniform in a real world MIMO system. When combined together they form the *channel transfer matrix*, **H**:

$$H = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix}$$

Each transmitting antenna will transmit a given set of symbols over a length of time given as L. This set gives us a transmitted signal vector, for a given antenna i, of x_i:

$$x_i = \begin{bmatrix} x_{i1} & \cdots & x_{iL} \end{bmatrix}$$

Similarly, each receiving antenna will receive a set of symbols over the same time period L. This received signal will depend on the interaction of the transmitted signal vector from each transmitting antenna with the channel transfer matrix as well as the amount of Gaussian white noise at the receiver. In vector form this is expressed as:

$$y_i = Hx_i + n_i$$

where y_i and n_i are the received signal vector and the received noise vector of a given receiver antenna respectively, and take the form:

$$y_i = \begin{bmatrix} y_{i1} & \cdots & y_{iL} \end{bmatrix} \qquad n_i = \begin{bmatrix} n_{i1} & \cdots & n_{iL} \end{bmatrix}$$

When the individual antenna vectors are taken together, they form the block transmission model:

$$Y = HX + N$$

or, in matrix form:

$$\begin{bmatrix} y_{11} & \cdots & y_{1L} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mL} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mm} \end{bmatrix} \begin{bmatrix} x_{11} & \cdots & x_{1L} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nL} \end{bmatrix} + \begin{bmatrix} n_{11} & \cdots & n_{1L} \\ \vdots & \ddots & \vdots \\ n_{m1} & \cdots & n_{mL} \end{bmatrix}$$

2. Spatial Multiplexing and MIMO Channel Capacity

The simplest way to model spatial multiplexing's effect on a MIMO system is depicted in Figure 6 where the MIMO channel is depicted as a number of independent, traditional single input, single output (SISO) data channels.
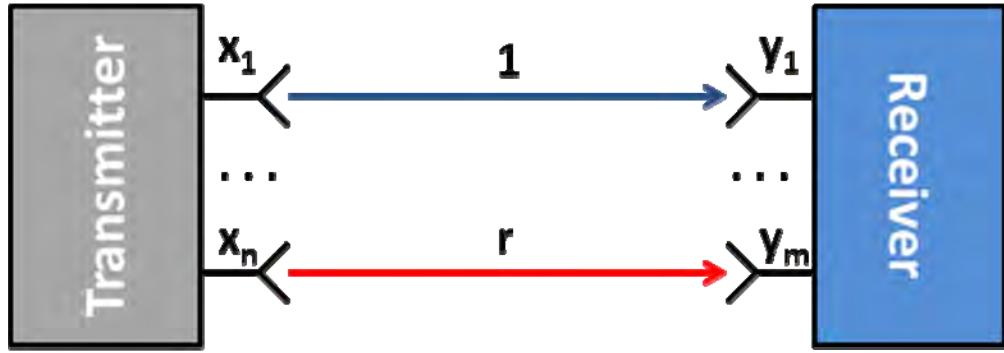
Figure 6.   Spatial Multiplexing in a MIMO system.

Here **H** has been decomposed into r number of linearly independent vectors or, in more mathematical terms, r is the rank of **H** and is the lesser of the amount of transmitting or receiving antennas.

$$r = \text{rank}(\mathbf{H}) = \min(n_t, n_r)$$

The literature focuses on the creation of a rectangular matrix $\mathbf{\Lambda}$ made of the eigenvalues of the singular value decomposition (SVD) of **H**:

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^*$$

where:

$$\mathbf{U} \in \mathcal{C}^{n_r \cdot n_r} \text{ and } \mathbf{V} \in \mathcal{C}^{n_t \cdot n_t}$$

Without going into detail on the math involved, $\mathbf{\Lambda}$ will contain r eigenvectors (λ_1 through λ_r). These eigenvectors can be thought of as the channel gains for the r independent channels of the MIMO system. Unfortunately, the math does not get simpler from there. In a real system, the values of **H** are randomly determined, and vary with time. Most literature assumes that these values are independent Gaussian variables. The crux of this is that the capacity of a spatially multiplexed system is a probabilistic function. Using Shannon's capacity equation as a base, the final capacity of a MIMO system is derived using the waterfilling algorithm to be:

$$C_E = \mathbb{E}\left\{ \sum_{i=1}^{r} \log\left(1 + \frac{\varrho}{n_t}\lambda_i\right) \right\} \quad (in \; \frac{bit/s}{Hz})$$

10

where $\mathbb{E}$ is the expected value of the function and ϱ is the average SNR at the receiver antennas. From this equation it is easy to see that increasing r will increase the total capacity of the system as it will sum more and more individual channel capacities.

The previous work assumed that there was sufficient spatial independence between the antennas to prevent spatial correlation. High spatial correlation reduces the overall channel capacity of the MIMO system as there is less physical volume for the independent channels to occupy. In this case, a rich multipath environment can be an advantage to a system. This is illustrated in Figure 7.
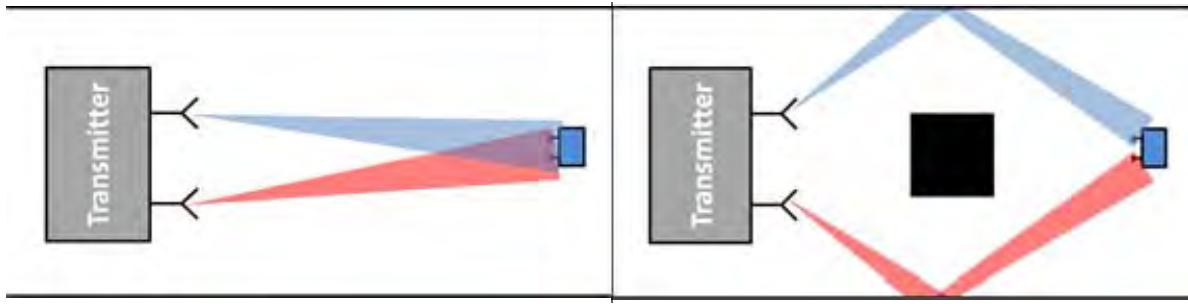
Figure 7.   In the system on the left, the line of sight path dominates the received signal, and the two data channels overlap at the receiver's antennas. This prevents the reciever from being able to separate them into two independent data streams. The system on the right shows a multipath rich environment, where non-line of sight paths dominate. In this case there is little, to no, overlap at the reciever's antennas and it can resolve the signals into separate data streams. If the transmitter had knowledge of the state of the communications channel, it would be possible for it to modify its transmission to increase this spatial independence.

3.   Transmission Diversity and Signal Reliability

Rather than use the transmitter and receiver arrays to create parallel data channels, it is possible to increase the reliability of a signal by transmitting the same symbols over multiple antennas. Sending redundant data streams is called transmission diversity, and is useful in areas with poor SNR at the receiver due to fading conditions, as increasing the amount of channels broadcasting the same symbol will decrease the chances that they will all experience critical fading. Figure 8 gives a basic illustration of this concept.
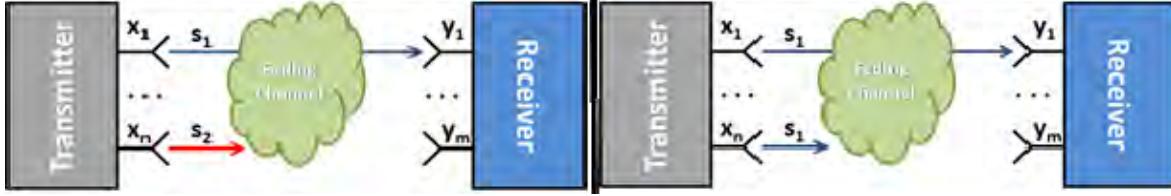
Figure 8.   The system on the left shows the separate data channels discussed in the previous section. However, in this scenario, the fading environment is such that one of the streams is attenuated past the receiver's threshold, and thus that data is lost leading to errors. The figure on the right demonstrates transmission diversity, with multiple antennas transmitting the same symbol. Enough of the transmitted symbol energy survives the fading environment to be detected by the receiver with no errors.

Figure 8 also demonstrates the fundamental tradeoff between maximizing channel capacity and maximizing channel reliability. Thus, it is impossible to maximize both spatial multiplexing and transmission diversity.

For an introduction to the math involved we will start with considering M identical versions of a given transmitted symbol s. This gives a set of received signal vectors:

$$y_i = \sqrt{\frac{q}{M}} h_i s + n_i \quad i = 1 \dots M$$

So the total amount of energy received for a given symbol s depends on M amount of independent observations of that symbol, each experiencing an independent amount of fading via h_i If a receiver is constructed that uses a process called maximum ratio combining (MRC), then the total post processing SNR for symbol s is given by the following function:

$$\eta = \frac{1}{M} \sum_{i=1}^{M} |h_i|^2 q$$

Based on this post processing SNR the probability of error for the transmitted symbol is:

$$P_e \leq N_s \left[-\frac{q d_{min}^2}{4M} \sum_{i=1}^{M} |h_i|^2 \right]$$

Where $\bar{N}$ is the number of nearest neighbors and d_{min} is the minimum distance in the set of available transmission symbols. From this most basic look at how diversity effects signal reliability it's clear that increasing the redundancy of the transmission, M, will lead to a larger negative exponent, which in turn will lower the probability of error.

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II.   CONCEPT OF OPERATIONS

A.   INTRODUCTION

The goal of this project is develop a cheap, and simple to use, UUV for clandestine data-relay in environments not conducive to traditional means of connecting with overhead national systems. Using a UUV for this function allows for multiple deployment methods as will be described in the following sections. A less complex system, such as a simple buoy or mine-like device, has much more stringent deployment requirements then a system that can be placed elsewhere and driven to its final location. This mission flexibility should prove valuable for mission planners.

In order to design such a system, we must first define how it will be employed, and the types of mission sets it will be used for in order to inform the hardware and software choices made during the design.

B.   BASIC FUNCTIONALITY AND ASSUMPTIONS

1.   UUV Functionality

For the purpose of establishing a concept of operations, and to inform the design later, certain assumptions will be made about what the UUV can do. First and foremost, the UUV will be able to communicate with both embedded systems in the jungle, and national overhead assets. Additionally the UUV will be assumed to have some sort of long term power supply allowing it to stay active for persistent missions. The UUV will have some sort of anchoring system to maintain its location in the targeted waterway, and this tether length will be adjustable to allow the UUV to change depth over time. Finally, it is assumed that the UUV is programmable with different mission parameters that will identify how it will communicate with both embedded systems and national assets.

While these functions are challenging engineering problems, there are a number of existing UUV systems that have been built that can perform them. A number of academic and commercial institutions have produced UUVs with flexible communications such as Hydroid's REMUS series, which can have wireless 802.11B

connectivity as well as iridium satellite communications.[10,11]   Virginia Tech's Autonomous Systems and Controls Laboratory (ASCL) has built a self-mooring AUV for long term oceanographic research.[12]   As for long term power for persistent missions, companies such as Liquid Robotics have produced vehicles that are able to harvest energy from their operating environments.[13]   Granted, Liquid Robotics' Wave glider series is a surface vehicle, but some of the same concepts can be applied to a UUV.

2.   Embedded Systems

The only assumptions made about the embedded systems for the purpose of this work is that they are able to communicate with the UUV, and that they can be programmed to match the same mission parameters as the UUV (i.e., transmission time windows.)

C.   MISSION CRITERIA

The use of this UUV can be broken in to two broad mission categories, persistent and non-persistent. Each has its own advantages and disadvantages that will have to be accounted for by operation planners when deciding to employ it.

1.   Persistent Missions

Persistent missions are precisely what the name implies; long-term mission sets where the embedded systems, overhead national systems, and area of operations, are static. When compared to transient missions, persistent missions require much more

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[10] Kongsberg Maritime Corporate Website, "Autonomous Underwater Vehicle - REMUS 100," Kongsberg Maritime,
http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/D241A2C835DF40B0C12574AB003EA6AB?OpenDocument.

[11] Kongsberg Maritime Corporate Website, "Autonomous Underwater Vehicle - REMUS 600," Kongsberg Maritime,
http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/F0437252E45256BDC12574AD004BDD4A?OpenDocument.

[12] Autonomous Systems and Controls Laboratory Website, "Self-Mooring AUV," Virginia Tech Autonomous Systems and Controls Laboratory, http://www.ascl.ece.vt.edu/HSAUV.html

[13] Liquid Robotics Corporate Website, "Wave Glider Concept," Liquid Robotics,
http://liquidr.com/technology/wave-glider-concept/.

planning for their use and placement in order to mitigate the risk of discovery that long term placement brings, as well as to counter the effects of river environments the UUV will be exposed to for long periods of time. For the purposes of this section persistent missions will be defined as those lasting a month or longer.

Since the primary driver to using a UUV for canopy circumvention is its stealth and its ability to perform clandestinely, finding a suitable area for placement is key for persistent use. Major rivers are the center of life for population in the areas where the UUV will be deployed. They are used for transport, communications, fishing, potable water, as well as simple recreation. Even if the UUV spends most its time on the bottom, surfacing only at night, if it is placed in a high traffic, or heavy use, area the likelihood of its discovery is high. It is imperative for planners to study river usage patterns in the operation area to find locations where the UUV will be less likely to be exposed to cast nets, drag lines, and divers.

An additional obstacle to the long term stability of the UUV is the river itself. Many major waterways in rainforests and jungles have severe currents, or highly fluctuating water levels. These factors will have severe impacts on both the UUV's position, and its ability to remain hidden. In many cases this data is seasonal, and so planners must be aware of the time table for their mission and plan accordingly.

Thus an ideal location for UUV placement would be one with little to no traffic, a steady, gentle current, and a relatively constant depth during the mission. Of course, the odds of finding a perfect location are low, so planners must balance these competing considerations and make an appropriate risk assessment.

While conducting persistent missions take much more planning and forethought than transient missions, they do offer more stability. Given the long term viability of the chosen location for the UUV, it allows for more careful employment of embedded systems in the jungle. This allows operators the time to experiment with system positioning in order to optimize the connection with the UUV and making the connection more robust.

2. Non-Persistent Missions

As the name implies, non-persistent missions are not intended for long term use, and are more expedient in nature. The main use for this mission set is to rapidly deploy a data relay capability for emergent collection needs, short-term observation, or to temporarily replace a compromised persistent mission UUV. Due to the shortened operation time, the risk of discovery is lower than for persistent missions in the area. Additionally, the non-persistent mission UUV will not require a location that is as environmentally stable as one for a persistent mission. For the purpose of this discussion, non-persistent missions will be defined as those lasting less than a month.

The primary concern for non-persistent missions, especially those responding to emergent requirements, is to find a location for the UUV that is within communications range of the embedded systems or operators. That is not to say that planners should ignore river usage patterns or current and tidal data, but the transient nature of the UUV's deployment should mitigate the risk of discovery or being carried away.

D. UUV DEPLOYMENT

Identifying the optimal position for UUV placement is in many ways the easy part. Placement of the UUV in the river or waterway may prove to be very challenging, especially if the destination is far inland. Four methods of deployment are identified and discussed here: portage, surface, submerged, and airborne.

1. Portage Deployment

Portage deployment involves the UUV being hauled by an operator through the jungle or rainforest, and being placed in the desired location via a small dive operation. Obviously this method is rife with concerns for mission planners.

Chief among these concerns is time. Tropical rainforests are some of the most unforgiving terrain for overland travel on the planet. This is compounded by the fact that roads and other infrastructure that would make travel easier in these areas is scarce, meaning that most of the transport would have to be done on foot. The crux of this is that deployment time may be measure in days or weeks. For this deployment method to be

feasible the UUV must be man portable, which adds a significant size and weight constraint to the final system design.

Despite these issues, portage deployment has a few advantages. First and foremost is accuracy of placement. Having an operator physically place the UUV in the desired location means that it can be done slow and methodically and can be checked for accuracy before during and after. Additionally, with operators in place for the deployment of the UUV, they would be able to vet the data used for placement of the system. It is possible for them to make in situ observations of location usage, current, and tides allowing them to verify or correct the original placement location. Portage deployments also have the potential to be the most clandestine of the three methods given their slower pace and employment of highly trained operators.

2. Surface Deployment

Surface deployment refers to the use of riverine or special operations naval assets to traverse a given river and deploy the UUV in the desired location via the use of divers. While lacking the speed of an airborne deployment, a surface deployment is much faster, comparatively, then a portage deployment. The use of divers in placing the UUV also means that its placement can be just as accurate as a portage deployment, which is vital to the success of a persistent mission.

However, surface deployments are not as inherently clandestine as a portage deployment. This is especially true if traditional riverine assets are used in the deployment of the UUV as the indigenous population will certainly notice the deployment craft, especially while it is conducting the actual placement dive. There are two ways to counter this weakness, speed, and deception.

Figure 9.   A U.S. Navy Mark V Special Operations Craft. (From [14])

The use of speed to help conceal the placement of the UUV is obvious. The faster the deployment is conducted from start to finish, the less time will be spent on location, which in turn reduces the likelihood of detection especially during low use periods. This method would be most effective when used in locations near US forces as the transit time for the riverine asset would be low and the indigenous populace would already be accustomed to seeing a U.S. vessel.

The alternative to speed is to use vessels that are normally found on the targeted waterway rather than standard U.S. assets. When deployed properly this "Q-Boats" should not arouse the suspicion of the indigenous population. The method will obviously be much slower than a speed deployment, but it is feasible that a Q-Boat could loiter in

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[14] Navy.mil, "Image: 090428-N-4205W-840.jpg," U.S. Navy, http://www.navy.mil/view_single.asp?id=71291.

the deployment area and conduct the same sort of in situ observations that portage deployment can, which would allow for validation or correction of the planned UUV position.

3. Submerged Deployment

The ability to deploy the UUV from a U.S. Navy ship offshore, and drive it up river to the desired location would be ideal because it would minimize the amount of equipment and personnel that would actually need to be carried into the targeted area thus vastly lowering the risk of detection. However, a UUV large and powerful enough to fight its way against a river, especially for long distances, would be large, expensive, and complex, which is counter to the stated goal of being small and cheap. Instead, if the UUV was to be dropped up river of the desired deployment area, it would not have to battle the current, and would require far less power to reach its intended destination.

To accomplish a submerged deployment, the UUV will be dropped up river of the desired location from either a shore location, or a watercraft of some sort, and then travel semi-submerged, with its antenna housing partially exposed. For maximum reliability an operator onboard a chase boat could drive the UUV to position, so that problems in transit can be identified and possibly corrected. Alternatively, with an exposed antenna housing, the UUV will be able to receive GPS signal allowing for an autonomous transit using a simple series of waypoints. When the UUV reaches the target area it will be commanded to dive and anchor to the bottom.

Obviously, the availability of this deployment method may be extremely limited given that it requires some sort of presence up river from the desired deployment location already, which may or may not be feasible. However, it may be possible to "piggyback" the UUV deployment with normal riverine traffic such as routine presence patrols that happen to travel up river of the deployment location normally.

Since the UUV will be travelling mostly submerged, it will be harder to detect during the deployment and, if combined with routine riverine traffic, should not draw any

unwanted attention. Additionally, a submerged deployment does not require any diving operations to place the UUV in the deployment location as the UUV can be commanded to the bottom.

However, without a diver to ensure proper placement, the accuracy of a submerged deployment is lower than a portage or surface deployment. This also means that the anchor may not be very secure either, which can lower operational lifespan of the UUV if it fails to hold.

4.   Airborne Deployment

Air dropping the UUV into the desired area is the most rapid method of deployment, and is most suitable for emergent temporary missions. Unfortunately, while very rapid, airborne deployment is also the least accurate and least clandestine of the three methods. An airborne deployment also requires an area of open water large enough to accommodate the circular error probable (CEP) of whatever airdrop system is used that may not be possible in extremely tight geography.

The Naval Postgraduate School's Snowflake project serves as a good reference of how an airborne deployment might be conducted. The Snowflake ADS is a miniature, precision airdrop system that uses a small onboard guidance package to autonomously guide a set of parafoils to a preprogrammed GPS position. The package is small enough that it can be delivered via a wide variety of platforms such as general purpose Cessnas, UH-60 helicopters, and even UAV's. The ability to deploy the UUV from non-military aircraft can help prevent arousing suspicion from indigenous population.

Testing conducted in May 2009 demonstrated a CEP of 30m for a single Snowflake drop. A year later, a Snowflake networked with other dropped Snowflakes and ground weather stations, dubbed Snowflake-N, demonstrated a CEP of 10m. While extremely accurate for an airdrop system, and certainly accurate enough to land in most large jungle waterways, CEP's of 10 and 30 meters do not match the precision of the divers in the portage and surface deployment methods. This accuracy issue can be exacerbated if the desired UUV position is near shore as the CEP may overlap the shoreline or areas too shallow to hide the UUV.

Figure 10.   Test version of the Snowflake ADS. (From [15])

Like the submerged method, the lack of human placement also means that there is no assurance that the UUV will properly anchor itself to the riverbed. This, combined with the possibility of landing in areas not conducive to the long-term survivability of the UUV, can lead to a significantly reduced on-station time of the UUV.

Airborne deployment can also be the most obvious of the three methods as the parafoils will leave evidence of something being dropped in the area. Additionally, without operators on the ground to clear the area of observers, it's possible that the drop itself may be observed, which will directly compromise the UUV.

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[15] Naval Postgraduate School Website, "Snowflake Home," No Author Given, http://www.nps.edu/Academics/Centers/ADSC/Projects/Snowflake/SnowflakeSystem.html,

Given the dynamics of airborne deployment, choosing a suitable location for the UUV is more complicated. Given the CEP for a system like Snowflake, especially the non-networked model, planners must determine the effective area of the targeted waterway that encompasses the CEP of the drop system. More than likely this will limit deployment locations to the centers of the waterways, and preclude the use of areas near shore that may be low traffic. Additionally the drop must anticipate the current of the waterway meaning that the drop system must be programed to land upstream of the desired deployment location and allow the current to carry the UUV to the destination.

a. Assisted Airborne Deployment

Assisted Airborne delivery is a hybrid between the portage and airborne methods of deployment. Rather than dropping the UUV into the targeted waterway, an assisted airborne deployment will drop the UUV in the vicinity of a team already on the ground. This team can then conduct a dive operation in the river to effect the final placement of the UUV.

Like a portage deployment, an assisted airborne deployment is extremely accurate given that the divers can precisely place the UUV. Communication with operators on the ground also allows for the drop to be conducted in a cleared area, which should prevent the UUV from being compromised, and allows for someone to collect the parafoils and other evidence of the drop, thus protecting the clandestine nature of the operation.

This method suffers from the same time issues as normal portage deployment due to the ground team having to transit to the drop area, and thus may not be suitable for an initial deployment. However, it does offer a good method of augmenting a team that it is already in place with UUV support.

E. MISSION EXECUTION

Planning for the mission execution primarily entails deciding how the UUV will communicate with the embedded sensors that it is supposed to network with. For the

purpose of designing this CONOPS, actual network protocols will not be discussed, instead two broad, communication methodologies will be discussed: burst and constant

1. Burst Communication

Since the primary concern with using a data relay UUV is maintaining a clandestine presence, limiting the amount of time that the embedded system and the UUV are in communication lowers the probability of the UUV being compromised. There are two primary reasons for this.

The first is that the UUV will have to be close to the surface in order to communicate with the embedded system, as its antennas will have to be out of the water for them to function. Having any part of the UUV exposed at the surface makes it vulnerable to observation and discovery. By programming the UUV to only communicate during small windows of time, preferably during periods of low waterway usage, it's time on the surface is greatly reduced, which in turn greatly reduces the chances of it being observed.

The second advantage to burst communications is that it lowers the amount of time the communications signals between the UUV and the embedded system can be observed. This is important as even with a highly directional antenna on the embedded system, its signals will be transmitting laterally through the jungle environment where they could possibly be detected through either actively searching by the target, or inadvertently through interfering with other communications systems in the jungle.

To affect burst communications, planners must determine how long they want their communications windows, and at what times of day they want them. The UUV can then be programmed to reel itself up and down its anchor tether to control its depth and breach the antennas.

The embedded sensors will also have to be programmed with the same transmission windows so that they only attempt to communicate with the UUV during the

desired transmission windows. This will also require that the embedded systems will have some sort of storage capability so they can collect and store data in real time for later transmission.

The drawback to this communications method is that the data is no longer real time, and windowing the transmission will limit total daily throughput of the data. This may not be an issue for a persistent collection mission, but if the objective is to monitor for indications and warnings burst communications may not be suitable. Time synchronization between the UUV and the embedded sensors and systems will also be a problem. GPS is the most common time synchronization source in distributed systems, but will not be available to embedded sensors. It should be possible to synchronize an embedded sensor's internal clock with GPS time before placement and, provided there is not significant drift, receive daily corrections from the UUV during the burst windows since the UUV should be able to receive a GPS signal when its antenna housing is exposed.

2. Constant Communication

Constant communications is exactly what the name describes. By keeping the UUV at the surface constantly it allows for the embedded system and the UUV to transfer data in real time and has a much higher throughput then burst communications. Of course this method of communications exposes the UUV to observation and discovery, thus compromising the mission.

Though inherently less clandestine than burst communications, constant communications may be suitable for transient mission of very short duration or in areas of little to no indigenous usage.

F. MISSION TERMINATION

In order to maintain the clandestine nature of the UUV mission it is important to properly terminate the mission so as to prevent it from being discovered or compromised.

1.   Recovery

Since the location of the UUV is known recovery is certainly a possibility. Recovery of the UUV precludes any chance of adversarial recovery and exploitation of the device, which is certainly an advantage. This method is most viable when there are operators already in the area who can recover the UUV. If recovery of the embedded systems is already planned at the conclusion of the mission, UUV recovery can easily be folded into that assignment.

2.   Destruction

If getting operators back to the location of the UUV is not operationally feasible, then self-destruction is an alternative method of preventing it from being compromised. Given the clandestine nature of the UUV any self-destruction should be thorough enough to ensure that nothing usable is left that could be used to indicate what its mission was either directly or circumstantially. This should include blanking any onboard information storage to destroy data, blow plugs that fill the UUV with water in order to achieve physical destruction, and releasing the anchor and letting the waterway carry the UUV away from the mission area.

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III. AN OPTIMAL UUV DESIGN

A. INTRODUCTION

Given the description of the mission, and concept of operations for a clandestine data relay UUV, this chapter will enumerate an optimal design for such a device. This design will then serve as a benchmark for comparison to existing military, and commercial off the shelf (COTS), subsystems that could be used to construct one.

B. BASIC UUV DESIGN REQUIREMENTS

- Man portable

- Able to travel semi-submerged for short distances, as well as dive and anchor on command

- Able to communicate with a wide variety of other systems

- Able to operate on station for at least two months

- Must have programmable mission parameters

- Must be able to change depth at anchor

- Must have multiple self-destruct mechanisms

C. MAIN BODY DESIGN

1. Size and Weight

Of all the deployment methods described in Chapter II, the portage method is the most restrictive on the size, shape, and weight of the UUV given that it involves an operator physically carrying it overland into theater.

A medium sized, Army type ALICE Pack, which serves as good baseline for what an operator might be using if faced with a long overland march through the jungle, has internal dimensions of 22" by 29" by 19", which when combined with the other gear the operator will need, doesn't leave much room to carry the UUV internally. It is possible however, to attach things to the frame of the pack and carry them below the main

compartment. Ideally, this would take the form of a weather tight case that could be strapped on. In order to prevent it from being too bulky the case shouldn't be much larger than the pack itself. This limits the case, and thus the device it carries, to dimensions in the range of 22" by 10" by 22".

The device's weight is, again, limited by the operator carrying the device into theater. Given the relatively small size of the device, keeping it less than 20 pounds should be sufficient. This of course does not include any peripheral gear required such as a computer of some sort to program the UUV in the field, and any data cables that may be required for initial programming.

2.   Shape

There are two general categories of shapes for underwater devices that were considered for this application. The first is a spherical type, not unlike a classic underwater mine. Since the UUV will spend much of its life stationary and moored to the bottom, this shape seems to make sense for this application. Additionally, a spherical type of UUV would be easier to carry, and a more accommodating internal volume to fit other system components. However, there are some drawbacks to this shape that preclude it from being used in this application. In order for the UUV to have an extended on-station time it will have to be able to power itself. The most obvious way of doing this is to take advantage of the river, and draw energy from the current. A spherical shape makes this difficult to do, as installing any sort of turbine or propeller in a sphere where it has optimum access to the current would interfere with the placement of other systems. Additionally, in order to accomplish a submerged deployment, the UUV will have to share some of the same basic characteristics as other semi-submersible UUV's.

Taken in aggregate, this means that the UUV will most likely have a traditional torpedo type shape. Besides being hydrodynamically superior to a spherical shape for submerged transits, a torpedo shape would align itself naturally with the current while at anchor, giving its propeller optimum positioning to generate electrical power. The only caveat to this shape is that it must be able to keep its antenna housing oriented so that it

will always be closest to the surface in order to ensure that the smallest amount of UUV is exposed during its collection/transmission windows. Figure 11 gives a basic external layout of the UUV:
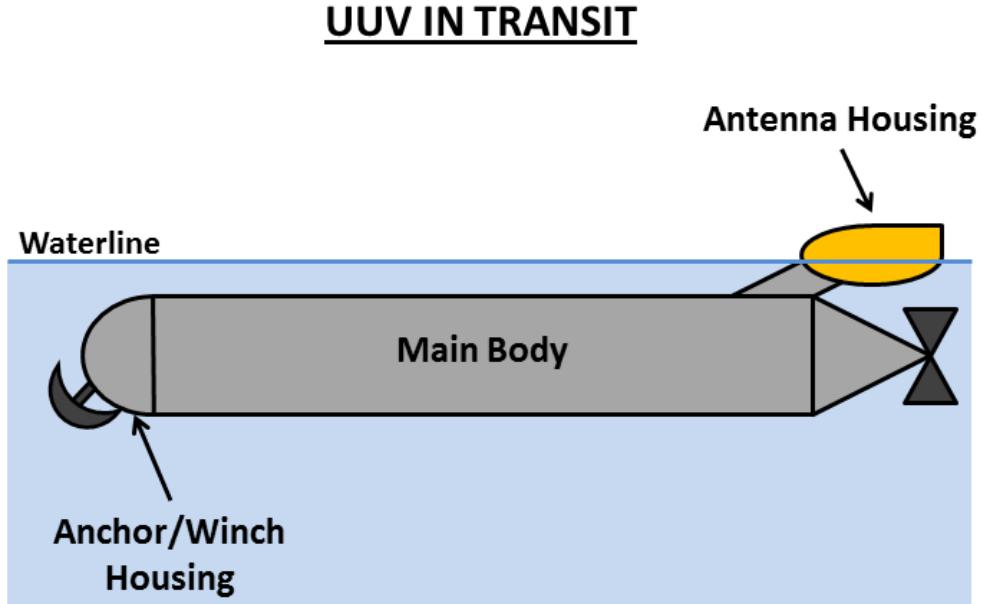
UUV IN TRANSIT

Figure 11.   Nominal UUV design in transit during a submerged deployment.

Given the dimensional constraints from earlier, and a torpedo shape, an approximate internal volume can be calculated to help inform further design choices. Of the 22in maximum length, 8in of it were assumed to be taken up by both the anchor winch housing and the UUV drive shaft, propeller, and steering gear. Additionally, the main body was assumed to have a 0.5in wall thickness leaving an internal diameter of 9". This results in an approximate main body volume of 890.64 in^3 (14.59 L).

Most standard torpedo shaped UUVs use a length to diameter ration (L/D) of 7 to maximize internal volume while minimizing drag. With a length of 22" and a maximum diameter of 10", this proposed design has an L/D of only 2.2. However, given the relatively short transit distances drag is not necessarily a concern, especially if it is travelling with the current during a deployment as is proposed in Chapter III.

D.   DATA LINK SYSTEM

The communications systems are the heart of the UUV, and their delivery to the proper location is the primary driver of its design. Ideally the UUV will contain at least two different radio systems, one for talking to the desired system embedded in the jungle environment (the client) and another for communication with the targeted overhead assets (the master).

1.   Radios

In order to ensure that the UUV will work with a variety of different embedded sensor systems, it must be able to accommodate multiple frequencies and use multiple modulation schemes. A software defined radio meets this requirement, and prevents costly, and time consuming, change outs of dedicated radio systems.

Since at a minimum the UUV will need to connect with two separate systems (one client, one master), the radio must be able to support two separate and independent channels. Using a multichannel radio will save space and weight when incorporated into the final design. Ideally, the UUV's radio will be able to accommodate many more channels allowing them to communicate with multiple client sensors in a distributed network, or possibly even feed multiple master systems with information.

Additionally, the UUV must be able to receive commands from a master system remotely, and forward commands to a client system, thus duplex communications is a requirement for any of the channels the UUV will be communicating on. Time-division duplexing is preferred due to less antenna overhead, and the ability to still use beam-forming methods to enhance communications in an already challenged environment.

2.   Antennas and Processing

Antenna choice for the UUV will have to depend on the desired frequencies of communications. While a universal antenna would be preferred for ease of use and cost of procurement, the jungle environment is difficult enough to communicate in, and any possible antenna gains must be exploited in order to maximize the effectiveness of the channel. Since communication with master systems will be easier, it should be possible

to use a one size fits all type antenna, such as a horn, oriented to send and receive from overhead. This antenna should be fitted to a self-leveling mount in the antenna housing so that it remains in the proper orientation regardless of the orientation of the housing. Figures 12 and 13 illustrate the desired nominal coverage areas.
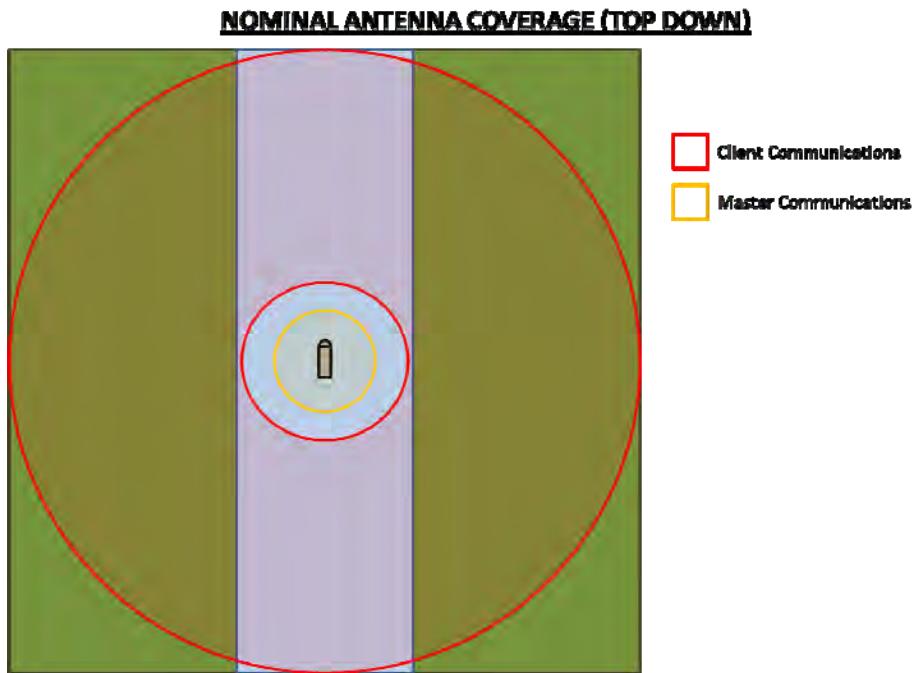
Figure 12.   Top down view of the nominal antenna coverage areas.
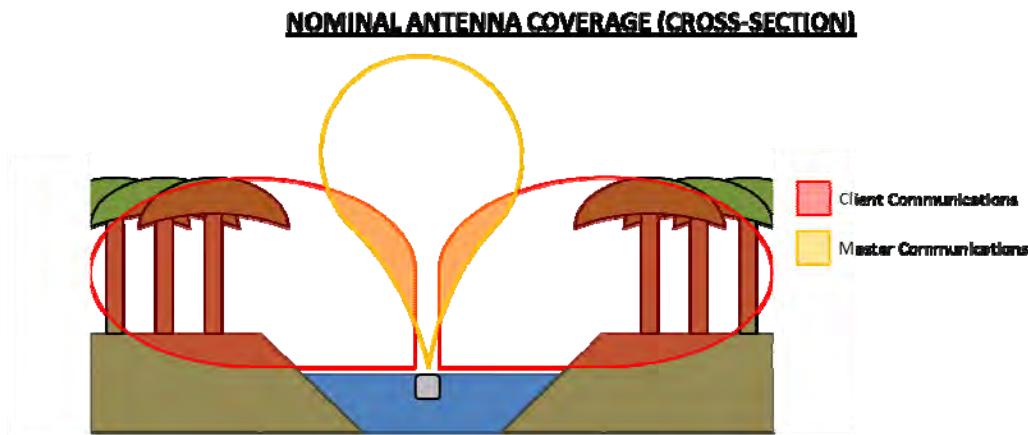
Figure 13.   Cross-sectional view of the nominal antenna coverage areas.

The nominal beam shape for client communications is based on the work by Tamir as discussed in Chapter I. Based on Figure 4, the signals received by the UUV from the client would primarily be the ones "leaking" from the canopy from the lateral ray traveling along the air-canopy boundary. This means that there is no need to try and maximize antenna coverage far into the forest, and instead the client antennas should focus up into the canopy where the signal should be arriving from.

In order to accommodate multiple client channels an array of small antennas, such as printed inverted "F" antennas (PIFA) that are extremely small and can be custom made for communications in the range of 1 to 10 GHz, will be used for client communications. An antenna array can be segmented to create multiple, independent, channels if necessary or can be used to enhance the effectiveness of a single channel through the use of beamforming. Beamforming also allows the UUV to scan the area electronically when attempting to establish client communications, which eliminates the need for any sort of mechanical scanning apparatus in the design.

The final advantage of using an antenna array is that it allows for the use of MIMO techniques in processing the client end communications. As was discussed in Chapter I, this should help to mitigate the environmental losses from the jungle and increase data throughput of the communications systems.

The antennas will be housed in a distinct compartment on the top of the UUV. This allows for the main body of the UUV to remain submerged while the antennas are above the water and transmitting. Additionally, having an antenna housing that is distinct from the main body of the UUV makes changing out the client side array much simpler if required. The housing itself will be made from standard radome material that is transparent at the desired communications frequencies. Ideally this housing could also be fashioned to look like river debris such as an exposed rock, or colored similar to the water in the river so as to help keep it covert and clandestine.

2.   Cryptographic Systems

In addition to basic radio communication, the UUV will require a robust cryptographic system that will allow it to talk with both its client and master systems.

Discussion of actual cryptographic methods or of specific cryptographic equipment is beyond the scope of this work. However, in order to be the most effective, the communications suite for the UUV must be able to handle various cryptographic techniques and be able to have different keys loaded by the operator, which would allow it communicate with a wide variety of clients and masters with different forms of cryptography.

E.   MISCELLANEOUS SYSTEMS

The UUV will require a number of other systems to support its operation once deployed.

1.   Mission Control Computer and Interfaces

With the requirement to be able to program different mission parameters into the UUV prior to deployment, some sort of central controller must be installed to coordinate the functions of the UUV's various system components in accordance with the desired mission parameters. This computer will also be the main controller for the UUV during a submerged deployment. The only real requirements for this computer are that it be easily accessible by the operator for both mission programming and for simple guidance. Ideally, the interface between the operator and the UUV should be just as clandestine and portable as the UUV itself. A smart phone application meets both these requirements.

A mission planning application would be able to capitalize on the ease of use most smart phone applications offer to encapsulate vital data (mission type, transmission frequencies, number of communications channels) allowing one relatively small file to be transferred to the UUV. Additionally, using a smart phone application would allow planners that may not be in theater to send mission parameters to operators in the field using existing mobile communications and data infrastructure. Since many modern smart phones use mini and micro-USB architecture, transfer of mission data could be done via a data port (inside the antenna housing to minimize the amount of openings in the main body) or by using a wireless communications standard such as Bluetooth, for which an antenna could easily be placed in the housing.

Steering and guiding the UUV could also be done via a Bluetooth connection using a smart phone application. Class 1 Bluetooth devices, at 100 mW, have a nominal range of 100 meters (approximately 328 feet) more than sufficient for short duration submerged transits using a chase boat and yet be short to make the chance of unauthorized detection low. Additionally, with data throughputs ranging from 0.7 to 2.1 MBits/s, a Bluetooth connection should be sufficiently fast to transfer positioning data and steering commands between the UUV and the operator. Obviously a smartphone application used to control the UUV in transit will not offer the same sort of precision as the dedicated command architectures of dedicated UUV control systems. Given that the UUV will actually be underway for only a short time, and should be transiting under the close supervision of the operator, the control and accuracy of a dedicated system does not outweigh the portability, ease of use, and relative covertness of a smartphone application vice having to carry dedicated command and control equipment.

At a minimum such an application needs to be able to display the UUV's position relative to the desired deployment location and be able to give simple commands (i.e., steer left, steer right, forward, reverse, dive to anchor). Additionally, the UUV itself needs to be able make rudimentary control decisions based on is GPS location in case the Bluetooth connection is lost in transit, or at the very least be able to maintain its position until the connection is reestablished.

Additionally, security and encryption in Bluetooth devices can be a concern. While the Bluetooth standard does include a basic encryption capability, any communication application developed for the UUV should also have additional security and encryption built into it in order to prevent unauthorized access to the device and to prevent any knowledge of what the UUV is doing from being intercepted.

2. Anchor and Winch

In order for the UUV to remain in place after it is deployed some sort of anchoring system is required. Ideally, this anchor would allow for normal use in muddy or silty bottom types, but also have some sort of hook or clasp mechanism so that it may be attached to roots and other partially submerged debris along the bottom for a more

secure hold. This anchor would then be attached to a heavy duty cable wound on a winch. This winch would then control the depth of the UUV, based on preprogrammed mission parameters, keeping it out of sight near the bottom when dormant or releasing just enough cable to expose the antenna housing when active. Figures 14 and 15 illustrate nominal active and dormant positions for the UUV at anchor.
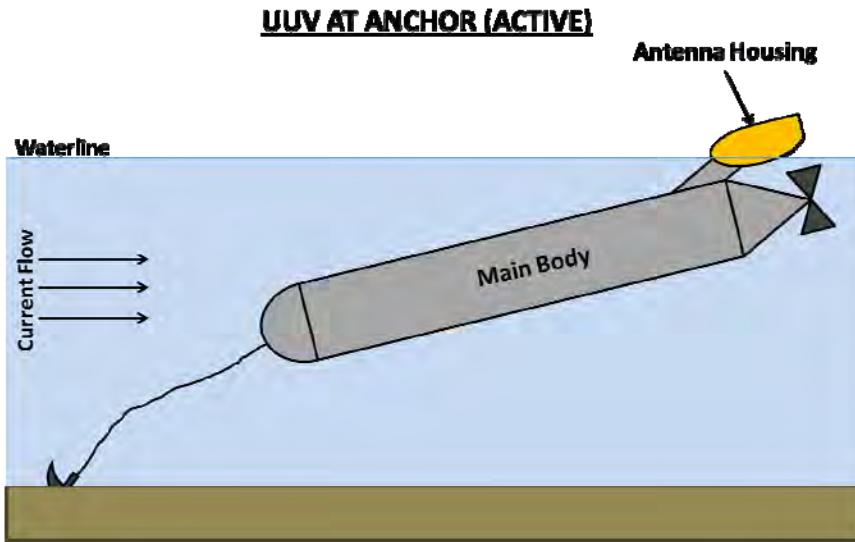
Figure 14.　While active, the winch will release enough cable to expose the UUV's antenna housing so it can communicate.
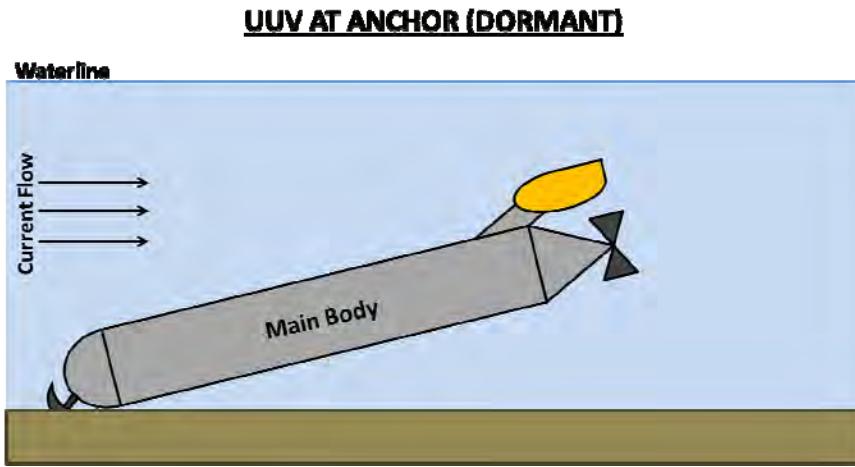
Figure 15.　When not broadcasting, the winch will reel the UUV in to prevent observation from the surface.

In order for the design to be of universal use, the winching system needs to be able to accommodate a variety of depths. Ideally, this would require around 30 feet of cable on the winch in order to give the system flexibility without requiring a bulky winching system that may exceed the volume allotted for it.

The problem with the anchor and cable design comes from the weight restrictions on the UUV both for carrying purposes and to limit the displacement the propulsion system must be able to handle. A cable, though easier to winch in and out then a chain, is not very heavy and thus puts emphasis on anchor weight and design to keep the UUV secure.

One way to lessen the carry load for portage deployments is to make the anchor detachable so that it can be carried by a different person. However, the anchor weight is still limited by the propulsion system of the UUV meaning that much more emphasis must be placed in shape and design of the anchor to make up for its lack of weight. The final design must be able to capitalize on the abundant debris set into the bottom of the targeted waterway to aid its ability to hold.

3.   Surface and Depth Sensors

In order for the UUV to be able to use its winch for proper positioning it must be able to determine when its antenna housing has breached the surface. This information would then be fed through the mission computer to command the winch to stop. While theoretically a fathometer of some type could be used to do this, in practice it would be difficult to use one.

Since a fathometer would be measuring from the river bottom, the UUV would have to know how deep the river is at any given time in order to know how much slack to let out from the winch. This knowledge is complicated by changing river levels over time and also by variations of current that will affect how much drag the UUV will experience and thus the amount of cable required for it to breach the surface. Therefore some sort of sensor mounted near the base of the antenna housing that can determine when it is exposed to air is preferred.

A series of simple conductivity sensors should work, as their measurement will change immediately after leaving the water. By analyzing the readings from several sensors, the UUV will be able to account for some of them being covered intermittently by waves, debris floating in the river, or by rainfall. The use of multiple sensors also adds redundancy in case one of them fails.

4. Self-Destruct Mechanisms

In order to prevent unauthorized recovery of the UUV, or the ability for the UUV's purpose to be deduced if it is recovered, there must be self-destruct safeties added to the system. These will take two, mutually supporting, forms: physical destruction mechanisms and data destruction mechanisms.

a. *Physical Destruction Mechanisms*

The physical destruction mechanisms will consist of a number of seals and entries into the main body of the UUV that can be preprogrammed to open after the conclusion of the mission, or commanded to open via the overhead assets. Opening these seals will flood the internal spaces of the UUV, not only to send it to the bottom of the river to make it hard to find, but also exposing sensitive internal components to river water. While freshwater exposure is generally not harmful to electrical components, cycling the power to the electronic components while submerged can lead to severe damage from shorts. Additionally, the water of some rivers is brackish in nature, and has a high enough salt content that prolonged exposure to it will corrode most of the more sensitive portions of the computers and radios.

b. *Data Destruction Mechanisms*

The prevention of unauthorized data removal from the UUV, accomplished through a media sanitization process, is in many ways more important than its physical destruction given that its computers and radios will contain a wealth of classified information such as frequencies and cryptographic keys for multiple controlled

systems. As such, the guidance set forth in *NSA/CSS Policy Manual 9-12: Storage Device Declassification Manual* is the standard used in planning for data destruction in the UUV.

According to the 9-12, simple overwriting (replacing of existing data with strings of nonsense data such as all 1's or all 0's) is not an acceptable form of classified data sanitization. In order to be 9-12 compliant, the information must be physically corrupted prior to release.[16] The easiest, and most effective, way of accomplishing this is through physically destroying the data with a device such as a shredder or incinerator. Since neither of those methods is possible in a UUV, it leaves degaussing as the only method available to sanitize the magnetic media.

Unfortunately, there is no way to address the solid state media (RAM and ROM) that will be present in the UUV's computers and radios in accordance with the 9-12 as the manual requires physical destruction[17] and degaussing will not work. This means the only recourse is to use a data overwriting process to eliminate any data that may be stored on it.

Taken together that means that there must be some form of degaussing equipment installed around all magnetic media in the UUV as well as some sort of data overwriting protocol installed to handle the RAM and ROM. These two processes will be set to activate in three different ways. The first two are the same as in the physical destruction mechanisms, a simple preprogrammed timer and or a command that destroys all the UUV's data when the mission window expires. The third method would be a triggered sanitization if an unauthorized person attempts to open the UUV. This fail safe method should be able to be deactivated via the encrypted Bluetooth connection that is used to upload mission parameters. The ability to communicate to the UUV with that connection requires possession of a device with an encryption key of some sort, which implies authorization to deactivate the safeguard and enter the UUV's casing.

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[16] U.S. National Security Agency/Central Security Service, "Storage Device Declassification Manual (Manual 9-12)," 7.

[17] NSA/CSS, *Manual 9-12*, 4.

F. POWER, PROPULSION, AND STEERING SYSTEMS

While semi-submerged transit is a stated mission requirement for the UUV, it is not expected to be able to travel for long distances or at high rates of speed therefore the propulsion system should be a primary concern in the design. Given the mission parameters set forth in the beginning of this chapter the power system for the UUV is of much more importance, and will be the primary driver in making design decisions for the drive train.

1. Power System

In order to operate for long periods of time on-station, with no support, precludes the UUV from using any sort of fuel based power system such as a fuel cell which would require logistical support to keep operational. Instead the UUV will be powered by a high capacity secondary battery, such as a lithium ion system, that will use the movement of the river to recharge itself.

As was stated earlier, the UUV's shape will naturally orient itself parallel with the flow of the river, which will place its propeller in a perfect position to receive energy from the current. If allowed to freewheel while not engaged, the propeller will be used to drive an electric motor in reverse, which when attached to a rectifier can be used to constantly recharge the installed battery system. This is known as tidal stream generation, or stream generation, and has been used in industrial power generation applications.

With a constant power source such as the river's current, the UUV does not require an inordinately large battery for its operations. This should free up substantial internal volume for the other necessary components and subsystems. Lithium ion battery systems have high energy densities, ranging from 254-430 Wh/L.[18] Even at the lower

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[18] Grant Ehrlich, "Lithium-Ion Batteries," In *Handbook of Batteries (Third Edition)*, ed. D. Linden and T. Reddy, (New York: McGraw Hill, 2002), 35.

end of that range, dedicating a liter (or 6.85% of the approximate volume) of the UUV to the battery system should provide sufficient power for the short periods where the UUV will not be able to charge itself.

a. *Power Budget Analysis*

Since the ability for the UUV to draw energy from the current is vital to the success of any of the mission types as proposed in this work it is important to have a basis to understand the power generation requirements. Since this is just the initial design it is hard to say what the actual power requirements of any constructed data-relay UUV would be. However, Virginia Tech's miniature AUV provides a good approximate for the power consumption of some subsystems due to the similarities in size and function between it and this proposed UUV design.[19]

Due to the short amount of time the proposed UUV would be underway, and the short distances it will travel, underway considerations will be ignored as the UUV's power requirements at anchor will dominate the power requirements. Table 1 lists the estimated power consumption by the subsystems that would be active during the mission.

System	Power (W)	Duty Cycle	Average Power (W)
Anchor Winch (DC Motor)	44.4	0.4	17.76
Mission Control Computer	3.5	1	3.5
Master Communications			0.57[20]
Client Communications	10	1	10
		Total:	31.83

Table 1.   Estimated Daily Power Budget for a Constant Communication Type Mission

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[19] William Seely, "Development of a Power System and Analysis of Inertial System Calibration for a Small Autonomous Underwater Vehicle," (Master's thesis, Virginia Polytechnic Institute and State University, 2004), 11.

[20] HighSpeedSat.com, "Motorola 9505 Iridium Phone," No Author Given, http://www.highspeedsat.com/motorola-9505.htm.

The motor powering the anchor winch is by far the largest power draw, but during a constant communications mission it would only need to be active long enough to ensure the antenna housing was above the water. The average power for master communications was based on the average power output of the Motorola 9505 Iridium satellite phone. This should be a good estimate for the UUV as it can communicate with overhead assets in bursts rather than constant communications for simple data relay missions. Client Communications was estimated at 10 W it falls between the normal output powers of handheld and vehicle borne military radios.

The amount of power that can be generated by an unducted tidal stream generator is given by:

$$P = \frac{\rho A V^3}{2} C_P$$

where P is the total amount of power generated in Watts, ρ is the density of the water in kg/m^3, A is the swept area of the propeller blades in m^2, V is the velocity of the water current in m/s, and C_p is the power coefficient of the tidal generator system and will be a result of losses from blade inefficiencies due to the number of blades and their angle of attack in addition to losses in the inverter and charging system.

Though this equation it is possible to estimate what the minimum current required to meet the average power of the UUV from Table 1. Assuming a C_p of 0.70, a swept area of 0.032 m^2 (or a 4" propeller radius), and using the density of pure water (1000 kg/m3), the minimum current required to generate 31.83 W per day is 1.41 m/s or 2.74 knots.

2.74 knots is reasonable expectation for the current in a targeted waterway. Also, this minimum current will be lower in real world water systems since the water will have a higher density then pure water. The power requirements themselves will also be lower for burst communications missions as the UUV will spend more time dormant thus lowering the power consumed by both communications systems and the anchor winch.

Additionally, river currents are not constant and can fluctuate with the tides or based on seasonal forces like rain run-off. With proper mission planning, it is

possible to build the transmission windows around these lulls in the current so that the UUV is dormant when its power generation capacity is its lowest.

2. Propulsion System

Since the UUV will only be driven under its own power for very small periods of time, the propulsion system does not have to be very robust. Since the primary function of the propeller and its shroud will be to keep the UUV's battery charged, ensuring that it can accomplish that as efficiently as possible should be the primary design concern when choosing a given blade geometry. Additionally, the shroud should be designed to ensure that river debris does not foul the propeller and prevent it from meeting its power generation requirements.

3. Steering System

Again, since the UUV will only be driven under its own power for very small periods of time, the steering gear only needs to be sufficient to make basic course corrections during a submerged deployment. They also need to be able to dive the UUV to the bottom when it is commanded to anchor during a submerged or airborne deployment.

IV. SURVEY OF EXISTING TECHNOLOGY

A. INTRODUCTION

The field of UUV development is rapidly expanding and advancing as both military and commercial customers seek better tools for leveraging the undersea environment. Therefore a survey of current products, both government and commercial off the shelf, can frame the feasibility of the proposed UUV design from Chapter III.

B. OPERATIONAL UUVS

There are a number of man-portable UUV's that could serve as the basis for a data relay UUV. Most of these systems are designed around modular payloads, which would make installing internal components, such as radios relatively simple, and thus limit any required design modification.

1. iRobot/Nekton's Ranger and Ranger 15A

The Ranger AUV, developed by Nekton Research, is a well-known, low cost, and highly adaptable micro-UUV. Nekton was acquired by iRobot Corporation, which in turn has started development on the Ranger 15A model. The Ranger is designed for short range, short duration, reconnaissance and oceanographic missions.

a. Pros

With an overall length of 35.83", and a maximum diameter of 3.58", the Ranger is very close to the dimensions stated in section II.C.1.[21] Additionally, the UUV itself rated at less than 45 pounds making a portage deployment plausible even after the addition of internal equipment.

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[21] No Author Given, "15A Ranger," *Jane's Unmanned Maritime Vehicles and Systems* (2011), http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/binder/jumv/juwta188.htm@current&Prod_Name=JUMV&

Additionally, the Ranger already incorporates mission programming via a standard 802.11 WIFI connection. It also has a straightforward system design standard in order to make the development and integration of special sensors and subsystems easier.

b. Cons

While the Nekton Ranger has small antenna masts, the proposed Ranger 15A would require one to be fitted to the hull. Self-destruct ports would have to be added in order to facilitate the craft's physical destruction.

The standard 172 Wh Lithium-Ion battery provides only 8 hours of endurance, which is completely insufficient to meet even short-term mission requirements as defined in Chapter II.[22] Installing a propulsion system that can recharge via the environment would be required.

Finally, the Ranger does not support anchoring or bottom mooring. An anchoring/mooring system would have to be created and integrated into the UUV in order for it to achieve the requirement.

c. Comparison to optimal design

CATEGORY	RATING	COMMENTS
Size and Weight		While exceeding the ideal length, 35" is still feasible to carry in a portage deployment.
Hull Shape		Would require a mast to be affixed for the antenna housing and holes for self-destruct ports.
Anchor and Mooring		No organic anchoring or mooring capability.
Power/Propulsion		8 hour endurance insufficient without recharge capability.
Programmability		802.11 WIFI capability is sufficient for using small PDA devices to upload mission parameters in theater.

Table 2. Summary of Comparison of Nekton Ranger to Optimal Design

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[22] No Author Given, *15A Ranger.*

Figure 16.   The future iRobot Ranger 15A. (From [23])

Figure 17.   The earlier Nekton Ranger model. Notice the shrouded propeller and antenna mast. (From [24])

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[23] No Author Given, *15A Ranger.*

[24] No Author Given, *15A Ranger.*

2. Hydroid's REMUS 100

The REMUS 100 is the smallest UUV in Hydroid's REMUS model line that has seen widespread use by Navy's around the world for hydrographic surveys, mine clearance, harbor security, and salvage operations.

a. Pros

The REMUS 100 is a very popular and reliable UUV system, and is already a part of the United States' UUV fleet. Existing personnel experience, combined with the REMUS' ability to accept varying payloads, should make incorporating the data relay equipment relatively simple.

The REMUS 100's top speed is 5 knots, which should make even upstream deployments possible except in areas with excessive current.

Additionally, some REMUS 100's already have an antenna mast installed, which may be able to be adapted for the data relay UUV's antenna housing. However, it should prove insufficient, Hydroid has proved willing to do custom design work for government customers.[25]

b. Cons

While the REMUS 100 is the smallest of the REMUS models, and is a man-portable system, its 54" length and 80 pound base weight would make it very difficult to deploy via the portage method.[26] Additionally the REMUS does not have any self-destruct ports, so those would have to be added.

The standard REMUS model relies on pre-placed acoustic beacons for navigation. Obviously, this is unsuitable for a clandestine data-relay mission. It is possible for the REMUS to use GPS waypoints for navigation but this will incur extra cost during acquisition.

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[25] No Author Given, "REMUS 100," *Jane's Underwater Warfare Systems* (2011), http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/binder/jumv/juws2192.htm@current&Prod_Name=JUMV&

[26] No Author Given, *REMUS 100*.

The REMUS 100 is power by a Lithium-Ion battery system that is rated at 22 hours of endurance, which alone is insufficient for even short duration relay missions. The REMUS 100 does sport a traditional propeller for propulsion however that should make installation of a rechargeable system possible.

Lastly, the REMUS 100 has no anchoring or mooring capability. In order for the system to accomplish that one must be designed, integrated, and installed.

c. *Comparison to Optimal Design*

CATEGORY	RATING	COMMENTS
Size and Weight		Portage method not possible but small and light enough to be deployed via every other method in Chapter II.
Hull Shape		Though lacking self-destruct ports, the REMUS 100 has an existing antenna mast that may be capitalized. Additionally, 7.5" diameter should be adequate space for any required communications equipment.
Anchor and Mooring		No organic anchoring or mooring capability.
Power/Propulsion		22 hour endurance insufficient without recharge capability.
Programmability		Relies on proprietary mission programming system using laptop included with vehicle.

Table 3.   Summary of Comparison of REMUS 100 to Optimal Design

Figure 18.   The complete military REMUS 100 system. (From [27])

Figure 19.   A REMUS 100 being deployed by UK Royal Navy sailors. Notice the antenna mast on the UUV. (From [28])

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[27] No Author Given, *REMUS 100*.

[28] No Author Given, *REMUS 100*.

3. Bluefin Robotics' Bluefin-9/SeaLion

The Bluefin-9 is a man-portable UUV used extensively by US Navy Explosive Ordinance Disposal teams for shallow water clearance operations. It is built around a free-flooded architecture that gives it a slight negative buoyancy in salt water.

a. Pros

Since the Bluefin-9 is already a government program, it should be possible to obtain UUV's within the existing Navy acquisition system. It also means that there is existing personnel expertise in operating the vehicle that should make planning and deploying it simpler.

A free flooded architecture and natural negative buoyancy should make physical self-destruction of the UUV relatively simple.

b. Cons

With a length of 64.96", and a base weight of 119 pounds, the Bluefin-9 would be nearly impossible to deliver via a portage deployment.[29] Additionally, that much weight would also make an airborne deployment extremely difficult and impractical as well.

The Bluefin-9 is powered by a 1.5 kWh Lithium-ion battery system with a rated endurance of 12 hours. Like the previous UUV's surveyed, this is inadequate for even short duration missions.

Lastly, there is no organic anchoring or mooring capability with the Bluefin-9. In order for the system to be able to do it, a complete anchoring system must be developed and installed. Also, having a negative buoyancy means that the Bluefin-9 cannot remain stationary without sinking to the bottom. This means that even if the Bluefin-9 were anchored at the desired target location, it would not be able to return to

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[29] No Author Given, "Bluefin-9/Sealion," *Jane's Underwater Security Systems and Technology* (2009), http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/binder/jumv/juwsa030.htm@current&Prod_Name=JUMV&

the surface again to communicate without powering back on and driving itself to the surface. This could be corrected using foam, or other positively buoyant payload, but would waste payload space that might be needed for the anchoring and communications systems.

c. Comparison to optimal design

CATEGORY	RATING	COMMENTS
Size and Weight	RED	Size and weight preclude portage and airborne deployments.
Hull Shape	YELLOW	While the Bluefin-9 has an antenna mast, it's far enough forward that it would make functioning as in Figure 14 difficult.
Anchor and Mooring	RED	No anchor capability. Also, negative buoyancy means UUV would have to power-up and drive itself to the surface rather than simply winch itself up and down.
Power/Propulsion	RED	1.7 kWh battery insufficient and requires recharge system to be installed. Propulsion thruster would need to be replaced for recharge system to be installed.
Programmability	YELLOW	While the Bluefin-9 can be programmed and controlled via an RF, it uses a proprietary system and software.

Table 4.   Summary of Comparison of Bluefin-9 to Optimal Design

Figure 20.   A Bluefin-9 with a US Navy EOD team. (From [30])

C.   OPERATIONAL COMMUNICATIONS SYSTEMS

Given how essential effective communications, of both voice and data, is to modern military operations it is no wonder that there are a host of existing communications systems that could serve as the heart of a data relay UUV.   The following systems operate in the VHF range and offer high rates of data transfer and ad-hoc networking capability.   While HF communications generally perform better in the jungle environment, using a UUV for data relay will shorten the distances communicated over thus allowing for VHF systems to be used.

1.   Raytheon's MicroLight-DH500

The MicroLight-DH500 is the latest entry into Raytheon's MicroLight software defined radio family.   The MicroLights are intended to be small systems for use by

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[30] No Author Given, *Bluefin-9/Sealion*.

everything from infantry patrols to airborne assets. They offer flexible networking for both voice and data communications, and are interoperable with the Joint Tactical Radio System (JTRS).

a. Pros

The DH500 is both incredibly compact and lightweight. Off the shelf, the system is 19.4 cm by 6.6 cm by 4 cm (0.512 L or 31.25 in^3) and weighs 0.873 pounds without an installed battery so it should be relatively simple to fit into nearly any man-portable UUV.[31]

The system can communicate in three frequency bands, from 225-2000 MHz and establish multiple channels using TDMA, CDMA, or FDMA. Like the previous model

Additionally, the DH500 supports VoiP, data, and video communications with a data rate of up to 1 Mbit/s meaning that a relay UUV that integrated it would be able to support a diverse set of relay missions. The DH500 can serve as a hub for an ad-hoc network, which should make establishing communications with any embedded jungle systems simple especially during a burst transmission mission set where the network will need to be reestablished often.

b. Cons

The most significant problem with using the DH500 in a clandestine data relay UUV is its use of commercial grade AES encryption. According to Raytheon's own specifications, the DH500 is only approved for secure, but unclassified communications.[32]   However, AES encryption has been approved by the NSA for communications up to TOP SECRET. According to the Committee for National Security

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[31] No Author Given, "MicroLight{TM} Software-Defined Radio Family," *Jane's Military Communications* (2011), http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/yb/jmc/jmc_9999.htm@current&Prod_Name=JMC&

[32] No Author Given, *MicroLight{TM} Software-Defined Radio Family*.

Systems policy the NSA has to approve any AES system that is intended for use with classified information.

Though it's unclear why the DH500 is not approved for classified information, it might be possible to certify the DH500 is suitable for use in a clandestine data system. It might also be possible to modify the specific AES algorithm employed by the system so that it is suitable for classified data, though it's unclear what effects this type of modification would have on the through put of the system.

c. *Comparison to Optimal Design*

CATEGORY	RATING	COMMENTS
Size and Weight		Extremely small. Should be easy to fit inside even a small UUV.
Frequency Range		Large frequency range should allow for communications with many different systems.
Data Rate		1 Mbit/s is sufficient for data, voice, and video communications.
Channels		Supports multiple channel separation schemes.
Security		Only approved for "Secure but unclassified" data. May be possible to upgrade to classified data.

Table 5. Summary of Comparison of DH500 to Optimal Design

Figure 21.   A MicroLight-DH500. (From [33])

2.   Harris' AN/PRC-152

The PRC-152 is a handheld tactical radio, and is the first JTRS compliant system certified by the NSA for traffic up to the TOP SECRET level of classification. It has seen extensive use by U.S. forces in operations in both Iraq and Afghanistan.

a.   Pros

The PRC-152 is small and relatively lightweight with dimensions of 23.36 cm by 6.35 cm by 4.318 cm (0.614 L or 37.47 in^3) and a weight 2.402 pounds.[34] Being able to integrate the system into UUV should not be difficult.

The system uses to standard frequency bands, 30-512 MHz and 30-520 MHz, and a "High Band Option" or 762-870 MHz. As with most hand-held radios, the PRC-152 has a maximum power output of 5 W, with the high band being limited to 4 W.

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[33] No Author Given, *MicroLight{TM} Software-Defined Radio Family*.

[34] No Author Given, "AN/PRC-152(C) JTRS SCA Multiband Hand-Held Radio," *Jane's Military Communications* (2011), http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/yb/jmc/jmc_a063.htm@current&Prod_Name=JMC&

The PRC-152 supports both voice and data communications up to the TOP SECRET level, though precise throughput of the system is not advertised.

b. Cons

The PRC-152 does not offer any sort of real networking options. Additionally it does not support multiple simultaneous communications channels, and thus multiple PRC-152's would need to be installed in a data relay UUV in order for it to communicate with multiple embedded systems.

c. *Comparison to Optimal Design*

CATEGORY	RATING	COMMENTS
Size and Weight		Very compact and lightweight.
Frequency Range		Large frequency bands available, allowing for flexibility in systems it can communicate with.
Data Rate		Not advertised.
Channels		Does not support networking or multiple simultaneous channels.
Security		NSA certified up to the TOP SECRET level.

Table 6.   Summary of Comparison of AN/PRC-152 to Optimal Design

Figure 22.   An AN/PRC-152. (From [35])

3.   Rockwell Collins Government Systems' FlexNet-Four

The FlexNet product line is a JTRS compliant software defined radio communications architecture.   The FlexNet-4 model in particular is vehicle radio designed to function as a high data rate network backbone.

a.   Pros

The strengths of the FlexNet-Four are its networking capabilities. Rockwell advertises that the FlextNet-Four can host simultaneous voice, data, and video communications for up to 150 participants with a data throughput of 5 Mbits/s for UHF communications and 64 kbits/s in in the VHF range. The FlexNet-Four operates from 2-2000 MHz.

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[35] No Author Given, *AN/PRC-152(C) JTRS SCA Multiband Hand-Held Radio*.

Additionally the FlexNet-Four, as a vehicle mounted device, has a much higher output power then smaller dismounted communications system. Its maximum output of 50 W should ensure that it covers a much larger area then the smaller systems surveyed earlier.

b.   Cons

As a vehicle system the FlexNet-Four is rather large, measuring in at 15.39" by 7.48" by 14.50" (1669 in^3 or 25.48 L).[36] Fitting this system into some of the smaller man-portable UUV's will not be possible. It may be possible to remove the internal components of the system to better fit the payload space available.

Security is also a concern for the system, as it is not rated as a Type 1 device by the NSA. Rockwell purports to be able to embed user specific encryption, so it should be possible for the device to be loaded with encryption abilities sufficient for it to be used for classified communications.

c.   *Comparison to Optimal Design*

CATEGORY	RATING	COMMENTS
Size and Weight		The FlexNet-Four is designed to be a vehicle borne system. It is not suitable for very small UUV's.
Frequency Range		Operates from 2-2000 Mhz. Should be sufficient to communicate with a multitude of existing systems.
Data Rate		64 kbits/s up to 5 Mbits/s should be sufficient
Channels		FlexNet-Four is a four channel device that can host 150 separate users.
Security		Not rated as Type 1 device, though may be possible to upgrade its encryption

Table 7.   Summary of Comparison of FlexNet-Four to Optimal Design

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36 Rockwell Collins FlexNet Website, "FlexNet-Four Specifications," Rockwell Collins, http://www.rockwellcollins.com/sitecore/content/Data/Products/Communications_and_Networks/Commun ication_Radios/FlexNet-Four_H-V-UHF_Vehicular_Multichannel_Software_Defined_Radio.aspx

Figure 23.   The FlexNet-Four. (From [37])

[37] No Author Given, "FlexNet JTRS-Compliant Software Defined Radio," *Jane's Military Communications* (2010), 2011.http://client.janes.com.libproxy.nps.edu/K2/doc.jsp?t=B&K2DocKey=/content1/janesdata/yb/jmc/jmc _a189.htm@current&Prod_Name=JMC&

V. CONCLUSION AND RECOMMENDED FOLLOW-ON WORK

A. GAP ANALYSIS

Based on the survey of technology in Chapter IV, it is clear that there is a sufficient baseline to use in building a data relay UUV. However, as was identified previously, none of the existing systems is ready off the shelf.

The most pressing gap is the lack of a hybrid propulsion/power generation system that can both drive the UUV during deployment and also perform stream generation to power the UUV at anchor. The technology itself is not new; it is more that it has never been miniaturized and installed in a UUV before. Developing such a propulsion system is vital to meet the mission criteria set forth in the concept of operations in Chapter II.

Additionally none of the basic UUV systems reviewed have an anchoring or mooring capability. This is also a vital capability required to achieve the mission sets from Chapter II. As was mentioned in Chapter III, anchoring capability is not unheard of in UUV's, it's more a matter of finding a system small enough that it can be fit into the chosen base system and integrating self-anchoring into the UUV's control system.

The last main gap is the development of the antenna arrays that will be used for client communications. These arrays will need to be designed and constructed based on the specific amount of channels desired for client communications and the frequency ranges chosen.

B. CONCLUSIONS

This thesis presented the concept of using a UUV to conduct clandestine data relay in a jungle environment in order to circumvent the heavy canopy interference normally found in such locations. It also presented an ideal design for building such a device with some analysis of the various design options available.

Based on the results of the technological survey in Chapter IV the optimal design for the data relay UUV would be a man portable, self-anchoring system with the ability to use stream generation techniques to power itself while at anchor that can be delivered to

the desired location using multiple means. Additionally, it would contain a robust communications capability that can support rapid, ad-hoc networking for receiving data from a distributed network of sensors. It would be able to have mission parameters uploaded and modified in theater using a non-dedicated system, and would be controlled via either preprogrammed GPS waypoints, or through the use of the same non-dedicated system used to upload mission parameters. Finally, the UUV should be able to terminate itself either at the conclusion of its mission, or if it is tampered with, in order to maintain the covert and clandestine nature of its mission.

The ultimate goal of this project is for a cost effective UUV to be developed using as many existing systems as possible. Based on the very basic design specifications presented here, as well as the brief survey of existing UUV and communications systems, achieving this goal seems possible. The proliferation of small UUV's in the Navy offers plenty of systems to draw from in addition to the myriad of designs from private industry that can also be leveraged.

However, despite the abundance of existing Navy and COTS systems, the primary method of saving money on the design is to make the UUV just robust enough to accomplish its primary mission. Thus for the UUV to be successful there must be ample programmatic support to ensure that missions are planned efficiently, and that the proper method of deployment is used. Operators and planners must understand the capabilities, and especially the limitations, of the UUV. To that end, the concept of operations presented here in Chapter II is more than just a basic assumption of the mission sets any relay UUV must be able to accomplish, it is also a set of questions that any operator must be able to satisfy so that they can maximize the effectiveness of the UUV.

C.   FUTURE AREAS OF STUDY

Since both the CONOPS and UUV design presented here are only nominal, and laid out only as the foundation for a UUV program, there are plenty of areas for follow on work.

### 1.	CONOPS Work

As was mentioned earlier, the ability to build a cost efficient UUV means that there must be a considerable amount of focus placed on the front end of the program, namely the concept of operations and mission paradigms.

#### a.	*Mission Planning Tools and Models*

In order to aid mission planners in making appropriate deployment decisions, there needs to be some sort of planning tool that can take in vital information regarding the desired deployment area and present it visually so that the planners have a clear understanding of what the UUV will be able to accomplish. Examples of such information is the target waterway's current and tidal patterns, the topography of desired shoreline, estimated electromagnetic propagation variables based on seasonal data and communications frequencies, weather patterns, and river usage information from intelligence sources.

The mission planning tools should be able to aggregate this data and visually display estimated coverage areas for the UUV's radios based on its location. These tools should also be able to accept data on the clandestine sensors and radios that the UUV will be communicating with so that their placement can also be planned appropriately, or if they are already in place, to help inform the placement decisions of the UUV.

#### b.	*Deployment Testing*

The four deployment methods listed in Chapter II need to be tested with either a functional prototype of the UUV or, at the very least, a properly weighted mock up. With the portage method being the limiting factor in the size, shape, and weight of the UUV, collecting actual data from simulated portage deployments is vital to validate the size and shape assumptions made in this thesis. Additionally, the airborne method also requires testing in order to collect more accurate circular error probable data that can be added to the mission planning tools.

2. Design Work

Since the design presented in Chapter III has no prototype, a number of the design decisions need to be validated to ensure the proper trade-offs were made.

a. The Mission Planning Application

The idea of a mission planning application needs to be validated to see if it is possible to develop an application that is portable from the (presumably) Windows machines of the mission planners, to the smart phones of the operators, to the operating system of the UUV to enable a seamless communications chain between the three devices.

Besides the application's portability, its security must also be verified so that the use of commercial networking protocols such as Bluetooth can be used in a system containing classified information.

b. Submerged Deployment Communications

The use of a high powered Bluetooth connection being used over water to control a semi-submersible is untested, but using a single wireless standard and application to both upload data to the UUV, and control it underway is a vital cost cutting measure that prevents having to develop a unique, stove piped, control system that will experience only minimal use.

Being able to determine the power requirements as well as effective data throughput to a semi-submerged system will influence the final design of the UUV's navigation system.

c. Power System Specifications

The ability of the UUV to draw power from the river environment is vital to the success of the design. To that end, an explicit design that balances power requirements, battery size, motor size, and propeller geometry so that the UUV can most efficiently generate electrical power while anchored and still be able to conduct a submerged deployment is vital.

Additionally, while there have been a number of UUV's that have been able to draw power from the environment, but none have used stream generation methods. Significant engineering work would be required to modify the exiting propulsion system of whatever UUV model is chosen so that it can generate power.

d.   *Network Integration*

This work focused almost exclusively on the design of the UUV itself; however, it is only a small portion of the communications and collections network it is relaying data for. The UUV must be interoperable with existing sensors and radios that would be deployed in the jungle environment. In order to ensure this happens testing should be conducted with a number of these existing systems to find which radio systems can communicate effectively with them in order to determine the best model for installation of the UUV. Additionally, these radios should be tested in dynamic environments where they have to communicate with a number of different sensors simultaneously to ensure the UUV can handle communicating in a complex environment with multiple channels.

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